

Title: EQUATION OF STATE OF DENSE PLASMAS

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## Equation of State of Dense Plasmas

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### Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The objective of this project was to design, build, and carry out an experiment to measure the equation of state (EOS) of a dense aluminum plasma. The results from this experiment would provide the first EOS data at these conditions. Though we did not reach this goal, we have steadily progressed towards it by doing simulations, constructing the apparatus, and designing new diagnostic techniques that meet additional requirements discovered through the simulations. We have also been required to develop additional laser capabilities needed for producing the dense plasmas and for the x-ray diagnostics. These capabilities have been a research project of their own. This development has been promising enough that this effort is being continued as part of another LDRD project to study dense plasma physics and its importance to the Atlas AGEX facility.

### Background and Research Objectives

Dense plasmas have been a topic of interest to the scientific community for many years. The first work was motivated by astrophysics applications, specifically the equation of state of matter in white dwarf interiors. Many theoretical approaches have been developed to address this issue, but the problem in verifying these theories has always been the difficulty in doing experiments in this regime. These difficulties come from problems in producing uniform conditions in a dense plasma and then being able to diagnose it. We developed a new approach that addresses the problems of creating and diagnosing dense plasmas. This approach combines the exploding wire technique, which we developed to produce dense plasmas, with another technique used to allow good diagnostic access.

The basic physical properties of plasmas have been theoretically addressed long ago. However, the assumptions used for these plasma theories are based on the usually correct approximation that the coulomb interactions among the particles are very weak. At high densities, this is no longer true. As the density increases, the coulomb energy

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between particles becomes greater than their thermal energy and the plasma is said to be strongly coupled. Under these conditions, the ions in the plasma begin to behave more as a liquid than a gas. To correct for this behavior, this interaction energy must be taken into account. The usual method for addressing this is to apply theoretical models that have been developed for liquid metals to plasmas under these high density conditions.

An example of how the interactions of the particles are important can be seen by considering the equation of state for classical free particles. If these free particles interact through a  $1/r$  potential, then their equation of state is given by  $PV = 2/3 (K.E.) + 1/3 (C.E.)$  [1], where C.E. stands for the total correlation energy and K.E. stands for the total kinetic energy. If the correlation energy is small, then this reduces to the ideal gas law. However, when it is large, this term is an important part of the equation of state. So in a fundamental way, a measurement of the equation of state of the plasma is a measurement of the strength of the correlations in the plasma. It is also difficult to calculate, thereby making the theoretical uncertainty in the equation of state higher in this dense plasma regime than in other regions of parameter space.

Some theories have attempted to calculate thermodynamic properties, but most have been used to predict transport properties. Experiments have been done comparing electrical resistivity measurements to some models [2-4], but no data exist to compare to predictions of thermodynamic properties such as the equation of state. These theories are therefore untested in their ability to predict the EOS of a dense plasma. The purpose of our project is to produce the first data in this regime to provide such a test.

### **Importance to LANL's Science and Technology Base and National R&D Needs**

Dense plasmas are an important area of interest to the laboratory both from a basic physics point of view and to address issues as part of the Science Based Stockpile Stewardship (SBSS) role of the laboratory. Such dense plasmas are produced whenever material at normal conditions is rapidly heated. This occurs in the inertial confinement fusion area and also in experiments done on AGEX facilities to address weapons physics issues. Thus, understanding the properties of dense plasma enhances our understanding of the plasma state in general, but it also is important to the role of computing at the Laboratory. Los Alamos is perhaps the foremost laboratory in the world in terms of computing capability, but these powerful computers used to model all kinds of phenomena require databases that provide the simulations with the properties of the materials being simulated. The theoretical models used for providing the data in these databases is untested in this dense plasma regime and therefore limits the ability to calculate and predict

phenomena with these computers. Well-tested theoretical models would provide more confidence in these databases and improve the predictive capability of our computers.

### Scientific Approach and Accomplishments

To make a measurement of the equation of state of a material, one must determine three thermodynamic properties such as density, temperature, and pressure. Most EOS experiments on high energy density materials get around this by doing a shock experiment. In these experiments, the conservation of mass, momentum, and energy in the material that is shocked reduce the number of variables to be measured to two. The two variables measured are usually the shock velocity and the material velocity behind the shock. These are used to determine the density, pressure, and internal energy of the shocked material.

The approach we are taking is the shock method described above. The experimental details, however, are quite different from the usual experiment that uses a flyer plate to impact the material and launch a shock. We use a laser to launch the shock and we also launch the shock into a plasma, not a solid. This results in conditions produced in the shocked material not reached in the standard experiments. The conditions we expect to reach in these experiments are densities of  $\sim 1 \text{ g/cm}^3$  in aluminum at temperatures of 10s of eV. These conditions are in the strongly coupled plasma regime, where theoretical models are most uncertain.

A schematic of our experimental setup is shown in Figure 1. An aluminum plasma is produced using a 3-kJ electrical pulsed power machine to produce an electrical current of 100 kA. The time scale for the production of this plasma is  $\sim 200 \text{ ns}$  and the lead glass tamper that surrounds the aluminum wire insures that the plasma remains uniform for this time and the density remains high. When the aluminum wire is heated to a temperature of a few eV, the plasma expands into the vacuum. A  $100\mu \times 100\mu$  slit is placed in front of the expanding plasma to collimate the plasma plume and section out the uniform center of the plume. This flowing plasma exits the slit as a uniform aluminum plasma with a density of  $\sim 0.1 \text{ g/cm}^3$  and temperature of  $\sim 1 \text{ eV}$ . It is this plasma which serves as the initial conditions for the shock experiment.

Once the plasma leaves the slit, we shine an intense laser into the plasma from one side. The laser deposits its energy into the plasma in a very short-scale length, producing a very high pressure and launching a shock through the plasma plume. We can then determine the equation of state of the shocked plasma by measuring the density of the aluminum both ahead and behind the shock and by measuring the shock velocity. These measurements allow us to determine the pressure and internal energy of the shocked material. The technique we use for both measurements is laser x-ray back-lighting. This

technique uses a laser of high intensity incident on a solid target to produce x-rays. The x-rays pass through the plasma plume and are partially absorbed, with the amount of absorption depending on the density of the aluminum. They are then imaged on a detector, either an x-ray streak camera or x-ray CCD camera. The streak camera provides a time-dependent image and is used to determine the position of the shock front as a function of time, thereby giving the shock velocity. The CCD camera images the plume at one instant in time and is used to determine the density of the aluminum.

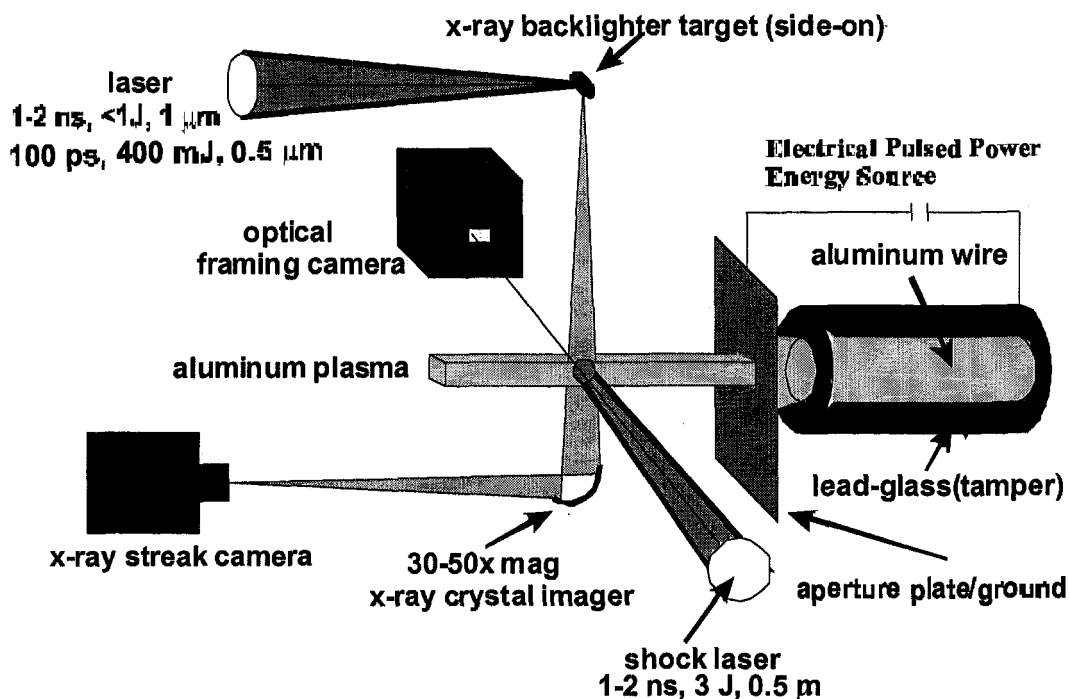


Figure 1. Schematic drawing of dense plasma equation-of-state experiment .

In the first year of the project, we began construction of the pulsed power machine to be used for heating the aluminum wire. This required using parts from a mothballed pulsed power machine and getting new capacitors, a new tank to contain the machine, and designing and building the electrical circuitry to provide the current to the aluminum wire. This part of the project was successfully completed in the second year. However, several additional changes needed to be made to the machine to provide reliable switching of the Marx units. The changes required were not completed until the third year, but now the pulsed power machine is operating reliably.

One of the first tasks done for this project was to simulate the experiment using a one-dimensional hydrodynamics code. The code used is capable of both local thermal equilibrium (LTE) and non-LTE atomic physics models and simulating the laser interaction with the material. The results of these simulations brought out some critical issues that needed to be resolved in order to carry out the experiment successfully. These issues were the thickness of the shocked material, the expected shock velocity, and the temperature and radiation emitted by the plasma.

The major problem illuminated by the calculations concerned the thickness of the shocked region of the plasma. The simulations showed that due to ablation from the heated plasma where the laser energy is deposited, the spatial extent of the shocked plasma is very small. This can be seen in the density profiles shown in Figure 2. These profiles indicate that the shock thickness is less than  $10\text{ }\mu\text{m}$ , even at late times. This was of smaller spatial extent than our original designs for the x-ray absorption measurements would resolve. These results led us to completely redesign the diagnostics to be used for the measurements and also required changes in the parameters of the lasers to be used. The development of these diagnostics and the design and construction of the laser systems required took the remainder of the project to complete.

To increase the spatial resolution of our x-ray absorption measurement, we proposed using spherically bent mica crystals as x-ray mirrors. These crystals could be used for a variety of x-ray energies with good optical properties. To get the resolution required for the density measurement, we needed to have a magnification of 15 for the imaging system. This could be done with a single crystal and a CCD camera. However, because of this increased magnification, we required more x-ray energy. Since this measurement requires using x-ray energies of 4.7 keV, we had to upgrade the laser system from a 100-mJ laser to a 400-mJ laser. We have successfully done this and this laser is operating and producing these x-rays by hitting a titanium target.

The hydrodynamic calculations also brought out the fact that the plasma temperature in the region where the laser energy was being absorbed rose to several hundred eV. This radiation would be transmitted through most of the plasma and would confuse any radiation measurements we would attempt. We originally intended to measure the shock velocity by looking for the shock breakout on the backside of the plume. These simulations indicated this technique would not be accurate enough due to radiation from the side of the plasma where the laser was incident. We therefore had to develop another technique for measuring the shock velocity. We decided to use the spherically bent crystals and laser back-lighting technique we were planning for the density measurement, but using a longer laser pulse

and a streak camera for the detector. This would allow us to determine the shock position as a function of time and from that obtain the shock velocity.

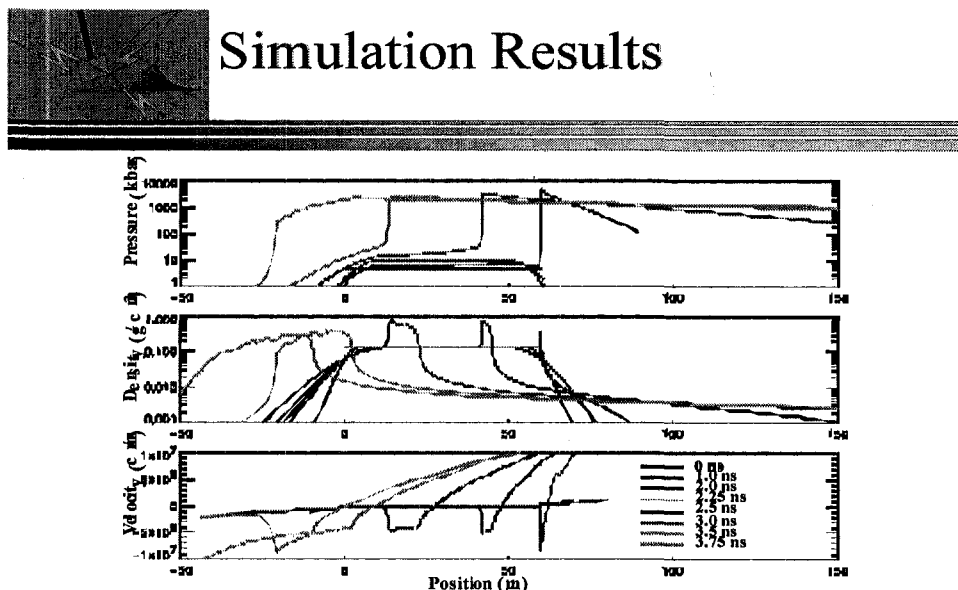


Figure 2. Time-resolved spatial profiles of aluminum plasma from one-dimensional hydrodynamics calculations.

The accuracy we could expect from this measurement is determined by the resolution of the streak camera, the magnification of the imaging system, and the shock velocities we expected to measure. From the simulations, we could estimate the shock velocities of interest and we measured the resolution of the streak camera to be  $90\ \mu$ . This meant that a magnification of 45 was required to get the time and spatial resolution we needed. This could not be done with a single crystal, so a two-crystal x-ray microscope was designed. This design is described in more detail in Workman, et al. (see project publications). The advantage of this system is that it provides very high spatial resolution with good optical properties. Though this technique had not been tested by the end of the project, we are continuing this work and are in the process of implementing the microscope on the experiment.

The simulations also showed that the shock velocities were of the order of a few  $\text{cm}/\mu\text{s}$ . To obtain the accuracy we needed for determining this velocity, we needed to sustain this shock for a period of  $\sim 2\ \text{ns}$ . We therefore needed the shock laser and the laser back-lighter to operate for this length of time. This again required a redesign of the laser being used for launching shocks in the plasma. We developed a technique for creating a variable pulse-length laser to produce both the shock and the x-rays needed to back-light

the plasma. This technique involves separating a 100-ps laser pulse into many pulses and then recombining them to produce a broader laser pulse. We are using this to produce laser pulses from 0.4 ns to 3.2 ns. A description of this technique by Roberts, et al. is in preparation for publication.

In summary, simulations done early in the project to better predict the conditions expected in this experiment led to a nearly total redesign of the experiment. It also indicated that a significant increase in the capabilities of the lasers was needed to perform the experiment. The diagnostic requirements for measurements of the densities and shock velocity were also proven to be much more stringent than originally believed, and this led to a significant effort on diagnostic development in the project. The result of this work has been the development of a novel approach to x-ray back-lighting that significantly enhances the spatial resolution capabilities of such diagnostics. The development of these lasers and diagnostics has provided enough confidence in the eventual success of this experiment that funding was obtained to continue the work. The eventual result should be the first equation-of-state data for material in the dense plasma regime.

## **Publications**

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